Year: 2016

Fracture strength of implant abutments after fatigue testing: A systematic review and a meta-analysis

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Abstract: PURPOSE The use of implants and their respective suprastructures to replace missing teeth has become a common therapeutic option in dentistry. Prior to their clinical application, all implant components have to demonstrate suitable durability in laboratory studies. Fatigue tests utilising cyclic loading typically simulate masticatory function in vitro. The objectives of this systematic review were to assess the loading conditions used for fatigue testing of implant abutments and to compare the fracture strength of different types of implant abutment and abutment-connection types after cyclic loading. MATERIALS AND METHODS Original scientific papers published in MEDLINE (PubMed) and Embase database in English between 01/01/1970 and 12/31/2014 on cyclic loading on implant abutments were included in this systematic review. The following MeSH terms, search terms and their combinations were used: ”in vitro” or ”ex vivo” or experimental or laboratory, ”dental implants”, ”implants, experimental”, ”dental prosthesis, implant-supported”, ”fatigue”, ”dental abutments”, ”cyclic loading”, ”cyclic fatigue”, ”mechanical fatigue”, ”fatigue resistance”, ”bending moments”, and ”fracture”. Two reviewers performed screening and data abstraction. Only the studies that reported, static fracture values before and after fatigue cycling of implant abutments, were included that allowed comparison of aging effect through cyclic loading. Data (N) were analyzed using a weighted linear regression analysis (α=0.05). RESULTS The selection process resulted in the final sample of 7 studies. In general, loading conditions of the fatigue tests revealed heterogeneity in the sample but a meta-analysis could be performed for the following parameters: a) abutment material, b) implant-abutment connection, and (c) number of fatigue cycles. Mean fracture strength of titanium (508.9±334.6N) and for zirconia abutments (698.6±452.6N) did not show significant difference after cyclic loading (p>0.05). Internal implant-abutment connections demonstrated significantly higher fracture strength after cyclic loading compared to external ones (internal: 774.0±582.3N; external: 481.2±137.5N; p=0.022). The mean fracture strength of all abutment types decreased significantly when number of loading cycles exceeded 1,000,000 cycles (<1×10(-6): 1047.0±751.3N; >1×10(-6): 556.7±317.6N; p=0.032). CONCLUSION The results of this meta-analysis, favour the use of internal implant-abutment connections in combination with either titanium or zirconia abutment materials. Number of cycles had a significant impact on the fracture strength after cyclic loading.

DOI: https://doi.org/10.1016/j.jmbbm.2016.05.011

Originally published at:
Coray, Rafaela; Zeltner, Marco; Özcan, Mutlu (2016). Fracture strength of implant abutments after fatigue testing: A systematic review and a meta-analysis. Journal of the Mechanical Behavior of Biomedical Materials, 62:333-346.
DOI: https://doi.org/10.1016/j.jmbbm.2016.05.011

Fracture strength of implant abutments after fatigue testing: A systematic review and a meta-analysis

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Short title: *Implant abutment strength after fatigue testing*

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ABSTRACT

Purpose: The use of implants and their respective suprastructures to replace missing teeth has become a common therapeutic option in dentistry. Prior to their clinical application, all implant components have to demonstrate suitable durability in laboratory studies. Fatigue tests utilizing cyclic loading typically simulate masticatory function in vitro. The objectives of this systematic review were to assess the loading conditions used for fatigue testing of implant abutments and to compare the fracture strength of different types of implant abutment and abutment-conncetion types after cyclic loading.

Materials and Methods: Original scientific papers published in MEDLINE (PubMed) and Embase database in English between 01/01/1970 and 12/31/2014 on cyclic loading on implant abutments were included in this systematic review. The following MeSH terms, search terms and their combinations were used: “in vitro” or “ex vivo” or experimental or laboratory, “dental implants”, “implants, experimental”, “dental prosthesis, implant-supported”, “fatigue”, “dental abutments”, “cyclic loading”, “cyclic fatigue”, “mechanical fatigue”, “fatigue resistance”, “bending moments”, and “fracture”. Two reviewers performed screening and data abstraction. Only the studies that reported, static fracture values before and after fatigue cycling of implant abutments, were included that allowed comparison of aging effect through cyclic loading. Data (N) were analyzed using a weighted linear regression analysis (α=0.05).

Results: The selection process resulted in the final sample of 7 studies. In general, loading conditions of the fatigue tests revealed heterogeneity in the sample but a meta-analysis could be performed for the following parameters: a) abutment material, b) implant-abutment connection, and c) number of fatigue cycles. Mean fracture strength of titanium (508.9±334.6 N) and for zirconia abutments (698.6±452.6 N) did not show significant difference after cyclic loading ($p>0.05$). Internal implant-abutment connections demonstrated significantly higher fracture strength after cyclic loading compared to external ones (internal: 774.0±582.3N; external: 481.2±137.5N; p=0.022). The mean fracture strength of all abutment types decreased significantly when number of loading cycles exceeded 1’000’000 cycles ($<1x10^{-6}$: 1047.0±751.3 N; $>1x10^{-6}$: 556.7±317.6 N; p=0.032).

Conclusion*:* The results of this meta-analysis, favour the use of internal implant-abutment connections in combination with either titanium or zirconia abutment materials. Number of cycles had a significant impact on the fracture strength after cyclic loading.

Keywords*:* Fatigue; Cyclic loading; Dental abutments; Dynamic loading; Fatigue resistance; Mechanical test

1. Introduction

The use of implants and their respective suprastructures to replace single or multiple missing teeth has become a common practice in dentistry. Although implant dentistry is already highly evolved, frequently new materials and designs are being continuously introduced. Today, vast numbers of implant systems with different components are available. While osseointegration is well established, the complications with implant-borne fixed dental prosthesis (FDP) and implant components are not completely eliminated (Strub and Gerds, 2003). In this context, not only the implant itself but also the durability of the type of abutment, the implant-abutment connection, and the abutment material have to be considered. With the advances in the computer-aided design/computer-aided manufacturing (CAD/CAM) technologies, high-strength ceramic materials are also incorporated as abutment materials as an alternative to traditionally used metal abutments in implant dentistry.

Since worldwide implant therapies are still considered costly treatment options, various prerequisites in terms of biocompatibility and mechanical durability needs to be met prior to their clinical application (Strub and Gerds, 2003). Among the mechanical properties, fracture strength or in other terms load-bearing capacity is considered to be one of the most important features for implant components. Static fracture tests are commonly applied to determine the strength of the abutments but in fact, they do not simulate the masticatory function, since certain factors such as time and the environment are excluded in such tests. Ideally, an in vitro test should simulate the clinical situation as close as possible so that translational meaning of the in vitro tests would be high (Alqahtani and Flinton, 2014). These requirements are best met by fatigue testing where implant components are exposed to cyclic loading (Dittmer et al., 2012). However, dental literature do not present controlled and standardized environment for cyclic loading conditions in implant dentistry. Although implant components are expected to fulfil ISO 14801 (ISO 14801., 2007) before they are launched in the dental market, an increasing number of studies are being published with diverse parameters used for cyclic loading, making comparison of durability of implant types and abutments nearly impossible.

The objectives of this systematic review therefore were to assess the loading conditions used for fatigue testing of implant abutments and to compare the fracture strength of different types of implant abutments before and after cyclic loading.

2. Material and methods

2.1 Search strategy

An electronic search at MEDLINE (PubMed) (http://www.ncbi.nlm.nih.gov/pubmed/) and Embase from 01/01/1970 to 31/07/2014 wad conducted for articles in English only. Following MeSH terms, search terms and their combinations were used for this search: “in vitro” or “ex vivo” or experimental or laboratory, “dental implants”, “implants, experimental”, “dental prosthesis, implant-supported”, “fatigue”, “dental abutments”, “cyclic loading”, “cyclic fatigue”, “mechanical fatigue”, “fatigue resistance”, “bending moments”, and “fracture” (Table 1). The MEDLINE search yielded 345 references to be screened for possible inclusion based on titles and abstracts (Fig. 1). A further manual search covering the period from 01/01/1990 up to and including 31/07/2014 was performed on the following journals: Clinical Implant Oral Research, Clinical Implant Related Research, Implant Dentistry, Journal of Dental Research, Dental Materials, International Journal of Prosthodontics, Journal of Prosthetic Dentistry, Journal of Prosthodontics, European Journal of Prosthetic and Restorative Dentistry, International Journal of Oral Maxillofacial Implants. In addition, hand searches were performed on bibliographies of the selected articles as well as identified narrative reviews to find out whether the search process has missed any relevant article. This added to one additional article to be involved in the review process.

2.2 Inclusion/Exclusion criteria

English language articles reporting on in vitro studies testing implant abutments and implant-abutment connection types, specifications of the investigated abutment materials, cyclic loading protocols, fracture strength or bending moments after the mechanical testing were included. Studies evaluating implant abutments in combination with an additional suprastructure such as a crown were excluded.

2.3 Selection of studies

Two independent reviewers (M.Z. and M.Ö.) performed the search process where 345 articles were found to have potential for possible inclusion in this systematic review. After screening the titles derived from the initial search based on the inclusion criteria, abstracts were screened and reviewed by both reviewers for meeting the inclusion criteria. Based on the selected abstracts, articles were subsequently obtained in full text. Thereafter, 60 articles were selected after reading their abstracts. The full texts of the chosen articles were then obtained and evaluated for inclusion in this review, leading to 33 relevant articles. Disagreements during the screening process were solved by discussion aiming for consensus.

2.4 Data extraction

The data collection form containing 21 items was created and used to evaluate the experimental environment of the in vitro studies described in the 33 relevant articles concerning cyclic fatigue tests. The variables were recorded and tabulated in Excel sheets. Variables of studies, which could not be extracted or calculated, were scored as 'not reported, nr'.

2.5. Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (version 22.0, SPSS Inc, Chicago, IL, USA). The inter-observer agreement with respect to the reporting of experimental conditions of the included abstracts before the consensus meeting is expressed as weighted Cohen's kappa. For descriptive statistics means and standard deviations, or medians and interquartile ranges in skewed distributions were noted. A weighted linear regression was applied for the meta-analysis of the following parameters: abutment material, implant-abutment connection type, number of loading cycles and fracture strength.

3. Results

3.1 Study selection

The publications qualified for inclusion are presented in Table 2. The Kappa score for agreement between the reviewers for screening of abstracts was 0.85. In the selected 7 articles (Boggan et al., 1999; Huang et al., 2005; Gehrke et al., 2006; Dittmer et al., 2012; Truninger et al., 2012; Stymmelmayr et al., 2013 Alqahtani and Flinton, 2014), a total of 165 experimental subgroups were identified where fracture strength results were reported in N. Finally, 7 articles met the inclusion criteria. All studies were in vitro studies published between 1999 and 2014. Excluded articles are listed in Table 4.

3.2 Testing parameters

Loading conditions in the selected sample revealed a large heterogeneity. In all of the included studies, forces were applied on the abutments in a different testing machine with either a stainless steel or a cobalt chromium indenter (Table 1). The loading forces varied between 10 N and 1995 N with a frequency of 2-15 Hz. While the specimens were loaded at 30 degrees in 6 studies (Boggan et al., 1999; Huang et al., 2005; Gehrke et al., 2006; Dittmer et al., 2012; Truninger et al., 2012; Stimmelmayr et al., 2013 Alqahtani and Flinton 2014), in one study the loading force was applied 45 degrees of axis (Alqahtani and Flinton, 2014). In three studies the temperature of the environment ranged between 5-55°C (Boggan et al., 1999; Truninger et al., 2012; Stimmelmayr et al., 2013). The cyclic loading environment was specified in 4 studies as 0.9% saline (Boggan et al., 1999), saliva substitute (Alqahtani and Flinton, 2014), lubricant film (Dittmer et al., 2012) or water (Truninger et al., 2012). The number of cyclic loading varied between 25’000 and 5’000’000. In three studies the number of cycles was below 1’000’000 (Boggan et al., 1999; Stimmelmayr et al., 2013; Alqahtani and Flinton, 2014;) and in four studies it was equal to or more than 1’000’000 (Huang et al., 2005; Gehrke et al., 2006; Dittmer et al., 2012; Truninger et al., 2012). The specimens were loaded at a crosshead speed ranging between 0.5 and 3 mm/min.

3.3 Fracture strength results

Fracture strength of the abutments before cyclic loading was assessed in three studies (Huang et al., 2005; Boggan et al., 1999; Dittmer et al., 2012) (Table 3a). All of these abutments were made out of titanium and fracture strength ranged between 430±59 N and 1955±18 N.

Fracture strength of titanium (508.9±334.6 N) and for zirconia abutments (698.6±452.6 N) did not show significant difference after cyclic loading ($p>0.05$).

Internal implant-abutment connections demonstrated significantly higher fracture strength after cyclic loading compared to external implant-abutment connections (internal: 774.0±582.3N; external: 481.2±137.5N; $p=0.022$) (Table 3b).

The mean fracture strength of all abutment types decreased significantly when number of loading cycles exceeded 1’000’000 cycles ($<1x10^{-6}$: 1047.0±751.3N; $>1x10^{-6}$: 556.7±317.6N; $p=0.032$).

4. Discussion

The use of implants as a substitute for lost teeth has become a common solution in dentistry. In order to decrease the failure rates of implants, the results of preclinical studies are considered in comparing performance and ranking of implant components. Especially the results of tests representing the worse-case scenarios help clinicians decide for implant systems that stay stable in long term clinical service. This systematic review was performed in an attempt to assess the loading conditions used for fatigue testing of implant abutments and to compare the fracture strength of implant abutments made of titanium or zirconia before and after cyclic loading. Based on the results of this study, not the abutment material but the implant-abutment connection type affected the results.

Cyclic fatigue loading test intend to investigate the mechanical durability of dental reconstruction materials prior to clinical trials in order to avoid costly interventions upon failures. Yet, to date the parameters employed by the investigators such as the number of fatigue cycles, loading jigs, frequency of loading, presence of humid environment, involvement of hydrothermal aging conditions show a great variation in the current dental literature. Although static fracture tests may help to screen the durability of implant components, one of the main causes of structural failure in implant dentistry is often as a consequence of fatigue. In that respect, cyclic loading could be considered a more clinically relevant testing approach. It has been reported that dental restorations fail more frequently under cyclic loading tests that are well below the ultimate flexural strength of these materials as opposed to the application of a single, relatively higher static load (Kelly et al., 2012). Thus, repeated stresses can predispose restorations to fail under fatigue. No universal standard is presently available for such test methodologies for reconstructive dentistry. In fact for implant dentistry, ISO 14801 serves as the only standard which requires $1x10^{-6}$ cycles with an upper load limit of 100 N at 30° axial loading. It has been previously reported that $2x10^{6}$ cycles correspond to approximately four years of normal occlusal and masticatory activity (Baldissara et al., 2010). In this sample, 5 of the selected studies practiced cyclic loading for 1 or more than $1x10^{-6}$ but 2 studies performed cycling less than $1x10^{-6}$. Nevertheless, in all studies fatigue loading tends to decrease the results regardless of the cyclic conditions. In addition, ISO 14801 requires embedding the implants with 2 mm implant neck exposure prior to loading in order to increase the torque effect. In this sample, only 2 studies loaded the specimens after such a modification. One study analyzed the influence of modifications on the fracture strength of internally connected zirconia abutments comparing unmodified abutments with modified ones and concluded that modifications after the sintering zirconia negatively affected the fracture strength results (Alqahtani and Flinton, 2014).

One major problem during the search process was the heterogeneity of MeSH and search terms related to cyclic loading or other fatigue related terms. In the dental literature, a great number of different terms are being used in order to describe some mechanical aging procedures for implant materials. This issue needs to be solved primarily so that future studies could report on identical search terms. Furthermore, in order to investigate the aging effect of cyclic loading on the durability on implant materials, the materials should be tested with and without exposure to cyclic loading. Unfortunately, the majority of the reason for exclusion was that the reconstructions were tested together with the abutments or that static loading was not performed after cyclic loading at all that did not give the possibility to compare the aging effect of cyclic loading. Crowns are tested on the abutments after some cyclic loading could not single out the real effect of aging procedures on the abutment since the principle forces are exposed on the reconstruction material and not on the abutment. There were altogether 7 studies selected through which the research questions could be answered to some extend. Such studies are usually costly and the number of these studies on abutments only, was less than those of the studies on crown-abutment combinations (n=18). Moreover, the number of specimens per group varied between 3 and 35. The statistical analysis required at least 6 specimens with identical test parameters to make more predictable assumptions.

The loading magnitude varied from 10 to 1995 N with stainless steel or cobalt chromium indenters with rounded tips. The diameters of the indenters were not enclosed in all studied. In fact, cone crack or Herzian crack formation especially on zirconia is highly dependent on the diameter and sharpness of the indenter (Lawn et al., 2001). Similarly, the temperature of the environment during cycling loading were either not reported or ranged between 5 and 55°C. Thus, temperature and medium related corrosion process could not be considered similar between the selected studies. Therefore, current studies regarding the fatigue strength of dental implant components should be evaluated cautiously considering the testing conditions. Some more systematic approach especially regarding the testing and reporting fatigue and loading conditions is needed when studying fatigue strength of implant components. Neverthless, interestingly, both titanium and zirconia abutment materials showed similar fracture strength after cyclic loading.

Zirconia is a densely sintered ceramic that offers chemically stable abutments with improved aesthetics in implant dentistry in combination with all ceramics crowns and FDPs. Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP; zirconia) offers good physical properties, including high flexural strength and high fracture toughness compared to other ceramic materials (Özcan et al., 2013). Unfortunately, the toughness of zirconia could decrease under aging conditions that are mostly related to phase transformation, where the tetragonal (T) phase is transformed into the monoclinic (M) phase. In this transformation, the energy absorbed by the zirconia matrix in the vicinity of the propagating crack is consumed by the T grains to transform into a M symmetry. The progress of the transformation leads to grain pullout and surface degradation, by the applied stresses, leading eventually to the failure of the device enhanced by the aqueous environment. Hence, dynamic loading could be anticipated to create more aging effect on zirconia compared to titanium. Interestingly, however, a dramatic decrease in the ultimate strength of zirconia was not observed in this sample. One explanation for this could be the abutment connecetion type that compansated for the possible aging factor on zirconia abutment, namely internally connected implant abutments exhibit significantly higher fracture strengths after cyclic loading compared to externally connected ones. In this studied sample, the number of subgroups with internal connections were higher with zirconia (n=99) than that of titanium (n=48). Also, the number of tested abutments with internal connectors (n= 147) were more in number than with external ones (n=18).

Stress applied during mastication may range between 441 N and 981 N, 245 N and 491 N, 147 N and 368 N, and 98 N and 270 N in the molar, premolar, canine, and incisor regions, respectively (Vallittu and Könönen 2000). The ultimate goal in measuring load-bearing capacity of materials is to know clinically whether they could endure chewing forces. The mean results of this study indicated values higher than that 400 N. Regardless of the brand, increased number of cyclic loading ($>1x10^{-6}$) decreased the fracture strength of all implant components tested, compared to $<1x10^{-6}$.

Based on the high results above the estimated chewing forces, current all-ceramic systems could be designated as favourable materials for posterior indications. On the other hand, from the technical point of view, the magnitude of the applied load with regard to the highest-level force in a fatigue test, should not exceed 50% of the ultimate strength of the material on trial. Unfortunately, this information was often not available in the references that performed static loading after fatigue.

Future studies should incorporate the fatigue component in the study set-up in order to deduce more clinically relevant information considering the ultimate strength of the material to be tested after fatigue. Clinically sufficient fracture strength values are not known for durable imokant components. The great variation in testing parameters and testing environment would continue to create the confusion in the dental literature. Since in the future, new studies are expected to appear in this field, the following items should be disclosed in in vitro studies:

- The abutment type, abutment material, loading conditions (jig dimensions, type, cross-head speed, indenter type, diameter), cyclic loading conditions (medium, temperature, loading magnitude, speed, number of cycles) should be defined precisely.
- The fracture strength data should be presented with confidence intervals, mean, minimum and maximum values with and without cyclic loading together with initial and ultimate fracture strength values.

5. Conclusions

From this systematic review study, the following could be concluded:

1. Current studies regarding the fatigue strength of dental implant components should be evaluated cautiously considering the testing conditions. Some more systematic approach especially regarding the testing and reporting fatigue and loading conditions is needed when studying fatigue strength of implant components.
2. Abutment material type (titanium versus zirconia) showed similar fracture strength after cyclic loading.
3. Internally connected implant abutments seem to exhibit significantly higher fracture strengths after cyclic loading compared to externally connected ones. Due to small sample size this conclusion must be considered with caution.
4. Regardless of the brand, increased number of cyclic loading ($>1x10^{-6}$) decreased the fracture strength of all implant components tested, compared to $<1x10^{-6}$.

Clinical Relevance

Internally connected implant abutments in conjunction with both titanium and zirconia abutments seemed to be more favorable considering long term fatigue durability based on the current available literature. Other clinical factors such as patient and site-specific factors, masticatory activity, aesthetic expectations which may be compromised by the gingival thickness, should also be considered when selecting abutments on dental implants.

Acknowledgements

The authors would like to thank Mrs. Dr. M. Gosteli from the main library of the University of Zurich for her assistance with the electronic literature search, Dr. M. Roos for her support with the statistical analysis.

Conflict of interest

The authors did not have any commercial interest in any of the materials used in this study.

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Captions to tables and figures:

Figures:

Fig. 1 Process of identifying the studies included in the review.

Tables:

Table 1a-b. Search strategy in **a)** MEDLINE and **b)** EMBASE applied for this review. #: search, MeSH: Medical subjects heading, a thesaurus word.

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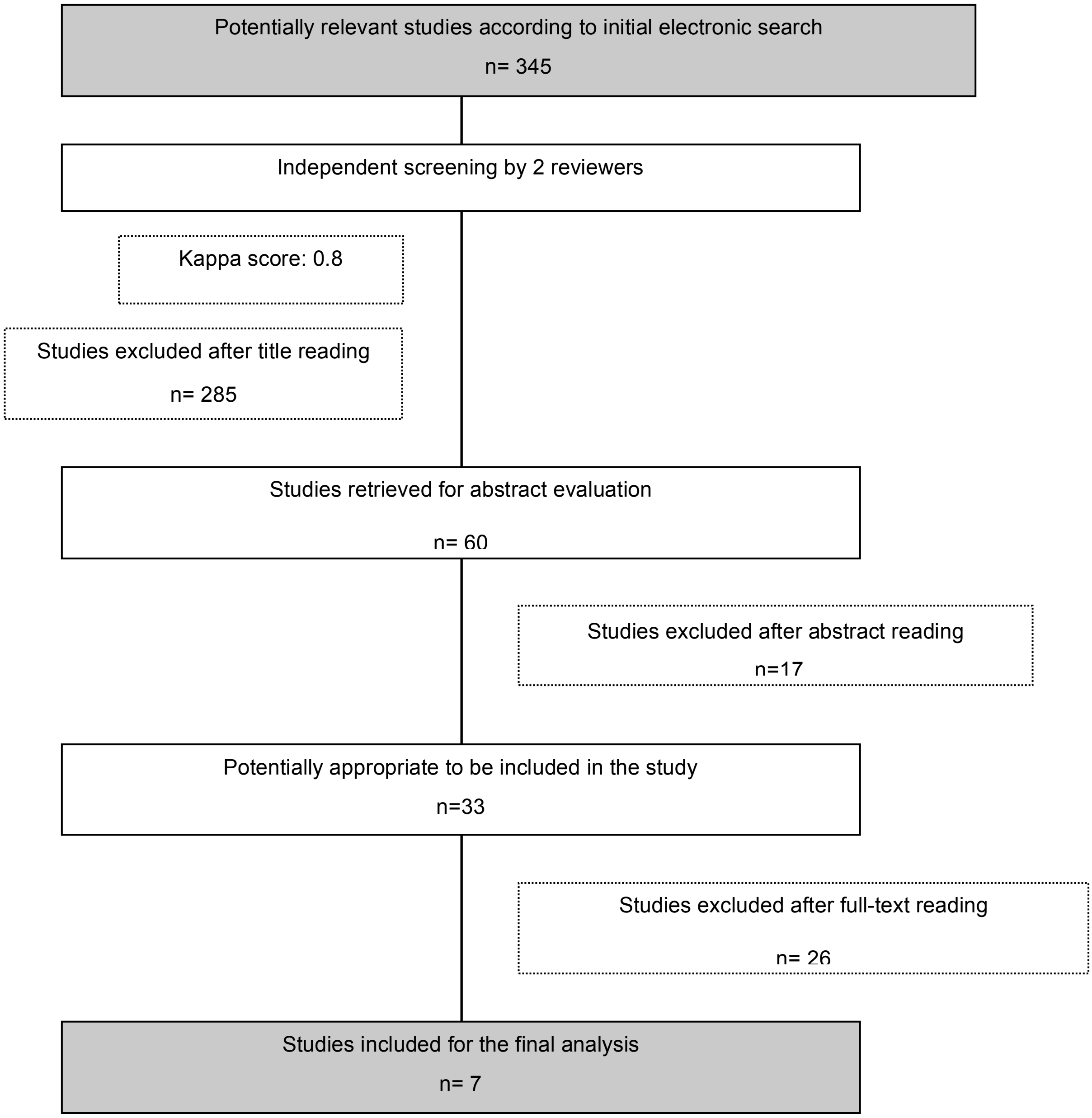

Fig. 1 Process of identifying the studies included in the review.

Tables:

Search	Literature search strategy	Results
1	Dental Implants/	14082
2	dental abutments/ or dental prosthesis, implant-supported/	11204
3	((dental adj3 (implant* or abutment*)) or (implant adj3 abutment*)).ti,ab.	10514
4	or/1-3	24961
5	"Prostheses and Implants"/ or Prosthesis Design/	70551
6	Implants, Experimental/	2561
7	(implant or implants or abutment*).ti,ab.	114482
8	or/5-7	168313
9	(dental or dentistry).ab,jn,kw,ti,sb.	188672
10	8 and 9	13200
11	4 or 10	27310
12	fatigue.ti,ab.	60056
13	(fracture adj3 resistance).ti,ab.	1498
14	(bending adj3 moments).ti,ab.	450
15	or/12-14	61853
16	Dental Stress Analysis/	13107
17	Stress, Mechanical/	52099
18	16 or 17	52099
19	In Vitro/	377193
20	("in vitro" or "ex vivo" or experimental or laboratory).ti.	523726

21	Search ((#7) AND #10) Filters: Publication date from 1950/01/01 to 2013/12/31; English	68
22	Search ((#7) AND #11) Filters: Publication date from 1950/01/01 to 2013/12/31; English	34
23	Search ((#7) AND #13) Filters: Publication date from 1950/01/01 to 2013/12/31; English	9
24	Search ((#7) AND #3) Filters: Publication date from 1950/01/01 to 2013/12/31; English	109
21	(("in vitro" or "ex vivo" or experimental or laboratory) adj3 (experiment or design or study or test)).ab.	106257
22	((cyclic or simulat*) adj3 (chewing or mastication)).ti,ab.	267
23	((fracture or cyclic or cylindrical or static) adj3 load*).ti,ab.	94954
24	(external adj3 hexagon adj3 implant).ti,ab.	109
25	or/19-24	931577
26	or/22-24	5181
27	11 and 15 and 25	159
28	11 and 18 and 26	316
29	27 or 28	379
30	Osseointegration/	7543
31	"in situ".ti,ab.	202588
32	30 or 31	210020
33	29 not 32	354
34	limit 33 to animals	12
35	limit 34 to humans	1
36	34 not 35	11
37	33 not 36	343
38	limit 37 to english language	332

Table 1a. Search strategy in MEDLINE applied for this review. #: search, MeSH: Medical subjects heading, thesaurus word.

Search	Literature search strategy	Results
1	'tooth implant'/exp OR 'tooth implant' OR 'dental abutment'/exp OR 'dental abutment'	2920
2	(dental NEXT/3 (implant* OR abutment*)):ab,ti OR (implant NEXT/3 abutment*):ab,ti 9,581	9,581
3	#1 OR #2	11214
4	implant:ab,ti OR implants:ab,ti OR abutment*:ab,ti	24961
5	dental:de,jt,cl,ab,ti OR dentistry:de,jt,cl,ab,ti	425,372
6	#4 AND #5	21783
7	#3 OR #6	22,818
8	fatigue:ab,ti	83952
9	(fracture NEXT/3 resistance):ab,ti	1,109
10	(bending NEXT/3 moments):ab,ti	478
11	#8 OR #9 OR #10	85,423
12	'mechanical stress'/exp	49,071
13	'in vitro study'/exp OR 'ex vivo study'/exp	4,208,113
14	'in vitro':ti OR 'ex vivo':ti OR experimental:ti OR laboratory:ti	581,645
15	(('in vitro' OR 'ex vivo' OR experimental OR laboratory) NEXT/3 (experiment OR design OR study OR test)):ab	103,436
16	((cyclic OR simulat*) NEXT/3 (chewing OR mastication)):ab,ti	114
17	((fracture OR cyclic OR cylindrical OR static) NEXT/3 load*):ab,ti	4,414
18	(external NEXT/3 hexagon):ab,ti	68
19	(hexagon NEXT/3 implant):ab,ti	37
20	#18 AND #19	31
21	#13 OR #14 OR #15 OR #16 OR #17 OR #20	4,585,922
22	#16 OR #17 OR #20	4,540
23	#7 AND #11 AND #21	112
24	#7 AND #12 AND #22	112
25	#23 OR #24	194

26	#23 OR #24 AND [animals]/lim	9
27	#23 OR #24 AND [animals]/lim AND [humans]/lim	1
28	#26 NOT #27	8
29	#25 NOT #28	186
30	#25 NOT #28 AND [english]/lim	180

Table 1b. Search strategy in EMBASE applied for this review. #: search, MeSH: Medical subjects heading, thesaurus word.

1st author	Title	Publication
Boggan RS et al.	Influence of hex geometry and Propsthetic table width on static and fatigue stentgth of dental implants	J Prosthet Dent 1999;82:436-440.
Huang HM et al.	Evaluation of loading coniditons on fatigue-failed implants by fracture surface analysis	Int J Oral Maxillofac Implants 2005;20:854-859.
Gehrke P et al.	Zirconium implant abutments: Fracture strentght and influence of cyclic loading on retaining-screw loosening	Quintessence Int 2006;37:19-26
Dittmer MP et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechanical loading	J Prosthodont Res 2012;56:19-24.
Truninger TC et al.	Bending moments of zirconia ad titanium abutments with internal and external implant-abutmet connections after aging and chewing simulation	Clin Oral Implants Res 2012;23:12-18.
Stimmelmayr M et al.	In vitro fatigue and fracture strenght testig of one-piece Zircoia implant abutments ad ziconia implant abutmets connected to titanium cores	Int J Oral Maxillofac Implants 2013;28:488-493.
Alqahtani F et al.	Postfatigue fracture resistance of modified prefabricated zirconia implant abutments	J Prosthet Dent 2014;112:299-305.

Table 2. Articles selected for the review that met the inclusion criteria.

Autor	Title	Year	Implant Type	Simulated marginal bone-level changes	Implant-abutment connection	Number of abutment specimens	Type	Material	Force (N)	Frequenc (Hz)
Alqahtabi et al.	Postfatigue fracture resistance of modified prefabricated zirconia implant abutments	2014	NobelReplace	nr	Internal	9	NobelProcera Abutment Zirconia	Zirconia	10 - 210	10
Alqahtabi et al.	Postfatigue fracture resistance of modified prefabricated zirconia implant abutments	2014	NobelReplace	nr	Internal	9	NobelProcera Abutment Zirconia	Zirconia	10 - 210	10
Alqahtabi et al.	Postfatigue fracture resistance of modified prefabricated zirconia implant abutments	2014	NobelReplace	nr	Internal	9	NobelProcera Abutment Zirconia	Zirconia	10 - 210	10
Dittmer et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechaical loading	2011	OsseoSpeed (Astra)	nr	Internal conical inferface/hexago, double hexagon	5	Tidesign	Titanium	up to 100	2

Dittmer et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechaical loading	2011	Semados (Bego)	nr	Hey-index flat to flat connextion with short interal conical matrix)	5	Sub-Tec Ti-Abutment	Titanium	up to 100	2
Dittmer et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechaical loading	2011	Screw-line promote plus (Camlog)	nr	Butt-joint/3 possible positions	5	Universal abutment 11mm	Titanium	up to 100	2
Dittmer et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechaical loading	2011	Akylos plus B14 (Friadent)	nr	Iternal conical inferface/no index	5	Balance posterior 0.75	Titanium	up to 100	2
Dittmer et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechaical loading	2011	MK III Groovy RP (Nobel Biocare)	nr	Hex-inedxed butt-joint	5	Easy abutmet Bmk syst Rp 1mm	Titanium	up to 100	2
Dittmer et al.	Influence of the interface design on the yield force of the implant-abutment complex before and after cyclic mechaical loading	2011	Standard implant (Straumann)	nr	internal conical interface/octagon	5	RN synOcta Tiabutment	Titanium	up to 100	2

Gehrke et al.	Zirconium implant abutments: Fracture strentght and influence of cyclic loading on retaining-screw loosening	2006	XiVE implants (Dentsply/Friadent)	3mm	internally hexed	7	Cercon zirconium implant abutments (Dentsply/Friadent)	Zirconia	100-450	15
Huang et al.	Evaluation of loading coniditons on fatigue-failed implants by fracture surface analysis	2005	BioTech One Pure titanium implants	nr	nr	35	cylindric abutment BioTech One	Titanium	319.52-718.92	15
Stimmelmayr et al.	In vitro fatigue and fracture strenght testig of one-piece Zircoia implant abutments ad ziconia implant abutmets connected to titanium cores	2013	Bego-Semados S (BEGO Implant) Systems Diameter 3.75 mm	nr	Internal hex	8	BeCe CAD Zircon HX, BEGO Implant Systems	Zirconia	120	1.2
Stimmelmayr et al.	In vitro fatigue and fracture strenght testig of one-piece Zircoia implant abutments ad ziconia implant abutmets connected to titanium cores	2013	Bego-Semados S (BEGO Implant) Systems Diameter 3.75 mm	nr	Internal hex	8	BeCe CAD Zircon HX, BEGO Implant Systems	Zirconia on titanium core (Titanium-aluminium-vanadium-alloy)	120	1.2

Stimmelmayr et al.	In vitro fatigue and fracture strenght testig of one-piece Zircoia implant abutments ad ziconia implant abutmets connected to titanium cores	2013	Bego-Semados S (BEGO Implant Systems) Diameter 5.5 mm	nr	Internal hex	8	BeCe CAD Zircon HX, BEGO Implant Systems	Zirconia	120	1.2
Stimmelmayr et al.	In vitro fatigue and fracture strenght testig of one-piece Zircoia implant abutments ad ziconia implant abutmets connected to titanium cores	2013	Bego-Semados S (BEGO Implant Systems) Diameter 5.5 mm	nr	Internal hex	8	BeCe CAD Zircon HX, BEGO Implant Systems	Zirconia on titanium core (Titanium-aluminium-vanadium-alloy)	120	1.2
Truninger et al.	Bending moments of zirconia ad titanium abutments with internal and external implant-abutmet connections after aging and chewing simulation	2010	Bonelevel RC implants (Straumann)	3 mm vertical bone loss simulated	internal	12	ETKON one-piece internal implant-abutment connection	Zirconia	49	1.67

Truninger et al.	Bending moments of zirconia ad titanium abutments with internal and external implant-abutmet connections after aging and chewing simulation	2010	Replace-Select system (Nobel Biocare)	3 mm vertical bone loss simulated	Internal	12	Procera abutments internal implant-abutment connection	Zirconia	49	1.67
Truninger et al.	Bending moments of zirconia ad titanium abutments with internal and external implant-abutmet connections after aging and chewing simulation	2010	Branemark MKIII RP Implants (Nobel Biocare)	3 mm vertical bone loss simulated	external hexagon	12	Procera abutments external implant-abutment connection	Zirconia	49	1.67
Truninger et al.	Bending moments of zirconia ad titanium abutments with internal and external implant-abutmet connections after aging and chewing simulation	2010	Standart Plus RN implants (Straumann)	3 mm vertical bone loss simulated	internal	12	CARES abutments with internal implant-abutment connection	Zirconia	49	1.67
Truninger et al.	Bending moments of zirconia ad titanium abutments with internal and external implant-abutmet connections after aging and chewing simulation	2010	Bonelevel RC implants (Straumann)	3 mm vertical bone loss simulated	internal	12	CARES abutments with one-piece internal implant-abutment connection	Titanium	49	1.67
Boggan et al.	Influence of hex geometry and Propsthetic table width on static and fatigue stentgth of dental implants	1999	Maestro implant system 4mm (BioHorizons Implantat Systems)	nr	external hexagon	3	Maestro	Titanium	96.6-966	15

Boggan et al.	Influence of hex geometry and Propsthetic table width on static and fatigue stentgth of dental implants	1999	Maestro implant system 5mm (BioHorizons Implantat Systems)	nr	external hexagon	3	Maestro	Titanium	195.5-1995	15

Table 3a. Cyclic loading test parameters for implant abutments.

1st Author	Modifications	Fracture strength (N) before fatigue	Number of cyclic loading	Temper ature	Environment	Load application axis	Indenter	Testing device	Fracture strength (N) after fatigue ± SD	Cross-head speed (mm/min)
Alqahtabi et al.	Unprepared	nr	250.000	nr	moist (saliva substitute)	45° off to axis °	nr	ADMET	567±35.4	1
Alqahtabi et al.	1 mm apical reduction/0.8 mm chamfer	nr	250.000	nr	moist (saliva substitute)	45° off to axis °	nr	ADMET	445.4±41	1
Alqahtabi et al.	1.5 mm apical reduction/0.8 mm chamfer	nr	250.000	nr	moist (saliva substitute)	45° off to axis °	nr	ADMET	430.5±39.4	1
Dittmer et al.	unmodified	430±59	1.000.000	nr	moist (lubricant film)	30° off to axis	hemispherical loading device (cobalt-chromium)	20K UTS Testsysteme	394±19	1
Dittmer et al.	unmodified	955±296	1.000.000	nr	moist (lubricant film)	30° off to axis	hemispherical loading device (cobalt-chromium)	20K UTS Testsysteme	407±65	1
Dittmer et al.	unmodified	891±85	1.000.000	nr	moist (lubricant film)	30° off to axis	hemispherical loading device (cobalt-chromium)	20K UTS Testsysteme	378±165	1
Dittmer et al.	unmodified	369±73	1.000.000	nr	moist (lubricant film)	30° off to axis	hemispherical loading device (cobalt-	20K UTS Testsysteme	304±9	1

							chromium)			
Dittmer et al.	unmodified	635±313	1.000.000	nr	moist (lubricant film)	30° off to axis	hemispherical loading device (cobalt-chromium)	20K UTS Testsysteme	347±24	1
Dittmer et al.	unmodified	456±54	1.000.000	nr	moist (lubricant film)	30° off to axis	hemispherical loading device (cobalt-chromium)	20K UTS Testsysteme	397±43	1
Gehrke et al.	unmodified	672	5.0000.000	nr	nr	30° off to axis	stainless steel rod	Instron 8872, Instron	268.8±37.8	1.27
Huang et al.	unmodified	798.8±4.1	5.0000.000	nr	nr	30° off to axis	nr	858 MiniBionix Axial Torsional Test System; MTS System	459.31±29.9	3
Stimmelmayr et al.	unmodified	nr	100.000	5° to 55°	nr	30° off to axis	roud stainless-steel stylus	CS-4, SD Mechtronic beim Dynamic loading oder 1445, Zwick/Roell bei fracture stregth testing	526±32	0.5
Stimmelmayr et al.	unmodified	nr	100.000	5° to 55°	nr	30° off to axis	roud stainless-steel stylus	CS-4, SD Mechtronic beim Dynamic loading oder 1445, Zwick/Roell bei fracture stregth testing	1241±268	0.5
Stimmelmayr et al.	unmodified	nr	100.000	5° to 55°	nr	30° off to axis	roud stainless-steel stylus	CS-4, SD Mechtronic beim Dynamic loading oder 1445, Zwick/Roell bei	1894±137	0.5

								.fracture stregth testing		
Stimmelmayr et al.	unmodified	nr	100.000	5° to 55°	nr	30° off to axis	roud stainless-steel stylus	CS-4, SD Mechtronic beim Dynamic loading oder 1445, Zwick/Roell bei fracture stregth testing	2225±63	0.5
Truninger et al.	unmodified	nr	12.000.000	5-50°	wasser	30° off to axis	corrosionfree steel indenter with rounded tip (ST V4A)	Zwick/Roell Z010, Zwick	663.4±105.6	1
Truninger et al.	unmodified	nr	12.000.000	5-50°	wasser	30° off to axis	corrosionfree steel indenter with rounded tip (ST V4A)	Zwick/Roell Z010, Zwick	859.4±125.6	1
Truninger et al.	unmodified	nr	12.000.000	5-50°	wasser	30° off to axis	corrosionfree steel indenter with rounded tip (ST V4A)	Zwick/Roell Z010, Zwick	571.6±128.8	1
Truninger et al.	unmodified	nr	12.000.000	5-50°	wasser	30° off to axis	corrosionfree steel indenter with rounded tip (ST V4A)	Zwick/Roell Z010, Zwick	759.8±118.2	1
Truninger et al.	unmodified	nr	12.000.000	5-50°	wasser	30° off to axis	corrosionfree steel indenter with rounded tip (ST V4A)	Zwick/Roell Z010, Zwick	1428.2±369.8	1
Boggan et al.	costomized, not specified, 2.7 mm diameter	966 ±7.6	Testing until fracture	37°	0.9% saline	30° off to axis	nr	servohydraulic test machine	350±57.7	0.51

Boggan et al.	costomized, not specified, 3 mm diameter	1955±18.2	Testing until fracture	37°	0.9% saline	30° off to axis	nr	servohydraulic test machine	625±57.7	0.51

Table 3b. Cyclic loading test parameters applied for testing implant abutments and fracture strength values.

Author	Title	Publication	Reason for Exclusion
Perriard J, Wiskott WA, Mellal A, Scherrer SS, Botsis J, Belser UC.	Fatigue resistance of ITI implant-abutment connectors. A comparison of the starad cone with a nocel internally keyed design	Clin Oral Implants Res 2002;13:542-549.	No fracture strength test after cyclic loading
Strub JR, Gerds T.	Fracture strength and failure mode of five different single-tooth imlant-abutment combinations	Int J Prosthodont 2003;16:167-171.	Abutment with reconstruction tested
Khraisat A, Abu-Hammad O, Dar-Odeh N, Al-Kayed AM.	Abutment screw loosening and bending resistance of external hexagon implant system after lateral cyclic loading	Clin Implant Dent Relat Res 2004;6:157-164.	Abutment with reconstruction tested
Butz F, Heydecke G, Okutan M, Strub JR.	Survival rate, fracture strength and failure mode of ceramic implant abutments after chewing simulation	J Oral Rehabil 2005;32:838-843.	Abutment with reconstruction tested
Khraisat A.	Stability of implant-abutment interface with a hexagon-mediaate butt joint: farilure mode and bendig resistance	Clin Implant Dent Relat Res 2005;7:221-228.	Abutment with reconstruction tested
Quek CE, Tan KB, Nicholls JI.	Load fatigue Performance of a single-tooth implant abutment system: effect of diameter	Int J Oral Maxillofac Implants 2006;21:929-936.	No fracture strength test after cyclic loading
Quek HC, Tan KB, Nicholls JI.	Load fatigue performance of four implan-abutment interface designs: Effect ot torque level and Implant System	Int J Oral Maxillofac Implants 2008;23:253-262.	No fracture strength test after cyclic loading

Steinebrunner L, Wolfart S, Ludwig K, Kern M.	Implant-abutment interface design affects fatigue and fracture strength of implants	Clin Oral Implants Res 2008;19:1276-1284.	Abutment with reconstruction tested
Kohal RJ, Finke HC, Klaus G.	Stability of Prototype two-piece Zirconia and titanium implants after artificial Aging: A in Vitro Pilot Study	Clin Implant Dent Relat Res 2009;11:323-329.	Abutment with reconstruction tested
Nguyen HQ, Tan KB, Nicholls JI.	Load fatigue performance of implant-ceramic abutment combinations	Int J Oral Maxillofac Implants 2009;24:636-646.	Bending moments tested
Magne P, Paranhos MP, Burnett LH Jr, Magne M, Belser UC.	Fatigue resistance and failure mode of novel-design anterior single-tooth implant restorations: influence of material selection for type III veneers bonded to zirconia abutments.	Clin Oral Implants Res 2011;22:195-200.	Abutment with reconstruction tested
Magne P, Oderich E, Boff LL, Cardoso AC, Belser UC.	Fatigue resistance and failure mode of CAD/CAM composite resin implant abutments restored with type III composite resin and porcelain veneers	Clin Oral Implants Res 2011;22:1275-81.	Abutment with reconstruction tested
Seetoh YL, Tan KB, Chua EK, Quek HC, Nicholls JI.	Load fatigue performance of conical implant-abutment connections	Int J Oral Maxillofac Implants 2011;26:797-806.	No fracture strength test after cyclic loading
Basílio Mde A, Butignon LE, Arioli Filho J.	Effectiveness of screw surface coating on the stability of zirconia abutments after cyclic loading	Int J Oral Maxillofac Implants 2012;27:1061-1067.	No fracture strength test after cyclic loading
Freitas AC Jr, Bonfante EA, Martins LM, Silva NR, Marotta L, Coelho PG.	Reliability and failure modes of anterior single-unit implant-supported restorations	Clin Oral Implants Res 2012;23:1005-1011.	Abutment with reconstruction tested

Freitas-Júnior AC, Rocha EP, Bonfante EA, Almeida EO, Anchieta RB, Martini AP, Assunção WG, Silva NR, Coelho PG.	Biomechanical evaluation of internal and external hexagon platform switched implant-abutment connections: An in vitro laboratory and three-dimensional finite element analysis.	Dent Mater 2012;28:218-228.	Abutment with reconstruction tested
Oderich E, Boff LL, Cardoso AC, Magne P.	Fatigue resistance and failure mode adhesively restored custom implant zirconia abutments	Clin Oral Implants Res 2012;23:1360-1368.	Abutment with reconstruction tested
Butignon LE, Basilio Mde A, Pereira Rde P, Arioli Filho JN.	Influence of three types of abutmets on preload values before and after cyclic loading with structural analysis by scanning electron microscopy	Int J Oral Maxillofac Implants 2013;28:e161-70.	No fracture strength test after cyclic loading
Foong JK, Judge RB, Palamara JE, Swain MV.	Fracture resistancce of titanium and zirconia abutmets: An in vitro study	J Prosthet Dent 2013;109:304-312.	Abutment with reconstruction tested
Freitas-Júnior AC, Almeida EO, Bonfante EA, Silva NR, Coelho PG.	Reliability and failure modes of internal conical dental implant connections	Clin Oral Implants Res 2013;24:197-202.	Abutment with reconstruction tested
Magne P, Silva M, Oderich E, Boff LL, Enciso R.	Damping behavior of implant-supported restorations	Clin Oral Implants Res 2013;24:143-148.	No fracture strength test after cyclic loading
Protopapadaki M, Monaco EA Jr, Kim HI, Davis EL.	Comparison of fracture resistance of pressable metal ceramic custom implant abutment with a commercially fabricated CAD/CAM zirconia implant abutment	J Prosthet Dent 2013;110:389-396.	Abutment with reconstruction tested
Boff LL, Oderich E, Cardoso AC, Magne P	Fatigue resistance and failure mode of adhesively restored custom metal-composite resin premolar implant abutments	Int J Oral Maxillofac Implants 2014;29:364-373.	Abutment with reconstruction tested

Mühlemann S, Truninger TC, Stawarczyk B, Hämmerle CH, Sailer I.	Bending moments of zirconia and titanium implant abutments supporting all-ceramic crowns after aging	Clin Oral Implants Res 2014;25:74-81.	Abutment with reconstruction tested
Nothdurft FP, Neumann K, Knauber AW.	Fracture behavior of zirconia implant abutments is influenced by superstructure geometry	Clin Oral Investig 2014;18:1467-1472.	Abutment with reconstruction tested
Rosentritt M, Hagemann A, Hahnel S, Behr M, Preis V.	In vitro performance of zirconia and titanium implant/abutment systems for anterior application	J Dent 2014;42:1019-1026.	Abutment with reconstruction tested

Table 4. Articles excluded after full-text reading that did not met the inclusion criteria.